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Air Force

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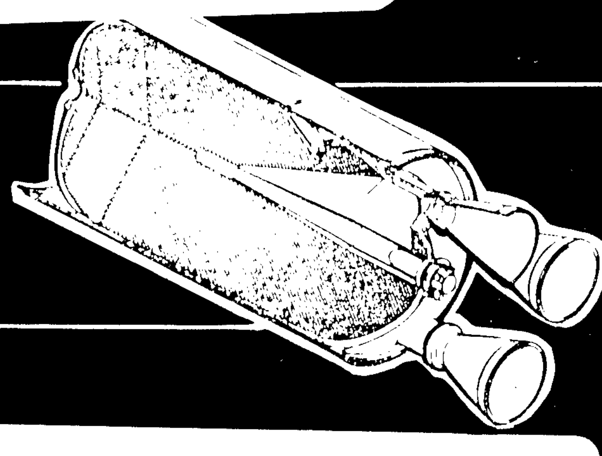
Studies & Analyses

EFFECTIVENESS OF THE MINUTEMAN II STAGE III REFURBISHMENT PROGRAM

JANUARY 1985



Air Force Center for Studies and Analyses
Directorate for Strategic Force Analyses
Missile Division

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EXECUTIVE SUMMARY

The attached diagram outlines the major developments concerning the Minuteman II Stage III thrust termination problem. As the first block in the diagram indicates, there have been 11 thrust termination failures in the combined testing of Minuteman I and Minuteman II Stage III motors. Although statistical analysis provides 99% confidence that Minuteman I thrust termination performance degrades with age, the low failure rate exhibited by both Minuteman I and II could support the hypothesis that the failures are due to manufacturing defects. This uncertainty regarding the nature of the failures prompted two programs: one to refurbish the stage's thrust termination ports and another to replace the stage should the refurbishment be inadequate.

Since initiating the refurbishment program, the Ogden Air Logistics Center has tested 31 Stage III motors without observing a failure of any type. However, 25 of the motors tested were Minuteman I motors, and questions arose concerning the equivalence of Minuteman I and II motor data.

If the motors are basically equivalent, the 31 successful tests provide 99.4% statistical confidence that refurbishing the thrust termination ports corrects the problem. On the other hand, if Minuteman I and II Stage III data must be treated separately, there is no evidence of an age-related problem in the Minuteman II thrust termination system. If, in fact, the failures are due to a manufacturing defect rather than an age-related degrade, the failure rate has not been significant in either the Minuteman I or Minuteman II.

Therefore, the refurbishment program has either been effective in correcting an age-related problem or it was unnecessary. In either case, the data do not support replacing the Minuteman II Stage III based on thrust termination considerations.

MM I/MM II STAGE III THRUST TERMINATION (TT) PROBLEM

PROBLEM	HISTORY OF TT TEST FAILURES MM I - 10/581 MM II 1/235 CAUSE UNKNOWN		
POSSIBLE CAUSES	AGE-RELATED	MM I PATTERN OF FAILURE — LOW FAILURE RATE	NOT AGE-RELATED. MANUFACTURING DEFECT
CONTINGENCY ACTIONS	REFURBISH MM I & MM II TT PORTS	PLAN FOR POSSIBLE MM II STAGE III REPLACEMENT - $924M, FY 86 - FY 95	
TEST RESULTS	POST REFURBISHMENT TT SUCCESS RATE MM I - 100% (25/25) MM II - 100% (6/ 6)		
RESIDUAL CONCERNS	MAJORITY OF TEST DATA BASED ON MM I. IS MM II SAME AS MM I?		
CURRENT SITUATION	IF MM II = MM I, POST REFURBISHMENT SUCCESS IS 100% (31/31) (99.4% STATISTICAL CONFIDENCE IN REFURB)	IF MM II ≠ MM I, MM II TT SUCCESS RATE = .996 (234/235) (NO EVIDENCE OF AGE DEGRADATION)	NOT A SIGNIFICANT PROBLEM. MM I TT SUCCESS RATE = .983 (571/581) MM II TT SUCCESS RATE = .996 (234/235)
DECISION REQUIRED		CONTINUE OR CANCEL STAGE REPLACEMENT PROGRAM	
OBSERVATIONS	CURRENT SITUATION DOES NOT SUPPORT FUNDING MM II STAGE III REPLACEMENT		

LOW TEST INVENTORY PRECLUDES ADDITIONAL SHORT TERM HIGH CONFIDENCE TESTING

PREFACE

The results of this study were presented to HQ USAF LEYW/XOOTS, OO/ALC MMG, HQ SAC/LGB/XPQ/XOK/DOMV/NR, and the 4220 WSES during December 1984 in support of a decision regarding the Minuteman II Stage III. This paper summarizes the analytical efforts and conclusions of the study.

INTRODUCTION

Testing revealed an increasing failure rate in the Minuteman I Stage III thrust termination system. Because of the similarity between the Minuteman I and Minuteman II Stage III, the Minuteman I tests raised the possibility that the Minuteman II Stage III thrust termination system may be degrading as a function of age. Concern over the reliability of this system prompted two programs: one to refurbish the thrust termination ports in both Minuteman I and II, and another to ultimately replace the entire stage should the refurbishment be ineffective. The apparent success of the refurbishment program has raised the question of whether or not the Minuteman II requires a new stage.

In addressing this question, this paper first provides a brief history of the thrust termination problem, describing its severity and the effectiveness of the refurbishment program. Following the background on the thrust termination ports is a description and statistical analysis of the available data. This statistical analysis, in conjunction with a sensitivity analysis of the required assumptions, leads to the conclusion that the data do not support replacing the stage based on thrust termination considerations.

BACKGROUND

Appendix 1 briefly describes the Minuteman II missile and outlines its major components. Of immediate concern to this analysis is the Stage III motor, which is diagramed in Figure 1 with one of its thrust termination assemblies highlighted by a circle. For greater detail, Figure 2 provides an expanded view of a single thrust termination assembly. The motor contains 4 such assemblies spaced 90 degrees apart and located above each of the 4 rocket nozzles. During flight, each thrust termination assembly explosively removes its corresponding thrust termination port cover upon mechanical separation of the reentry vehicle from the third stage. By opening a total surface area greater than that presented by the four rocket nozzle openings, exhaust gases vent through the thrust termination ports, reverse the motor's thrust and cause it to back away from the reentry vehicle.

Through the flight and static testing of Minuteman I and Minuteman II, the Ogden Air Logistics Center (OO/ALC) discovered that one or more of the thrust termination ports occasionally opened prematurely. In these cases, the thrust reversal was asymmetric, and the stage and attached reentry vehicle tumbled out of control. Therefore, premature thrust termination results in a catastrophic missile failure. For the Minuteman I, OO/ALC determined this failure mode was age-related; it occurred more frequently in older motors than younger ones. Based on the similarity between the Minuteman I and Minuteman II Stage III, OO-ALC suspected the Minuteman II would also experience an age-related degrade in performance. Consequently, the OO/ALC management initiated a program to refurbish the thrust termination assemblies in all the Minuteman II and remaining Minuteman I Stage III motors.

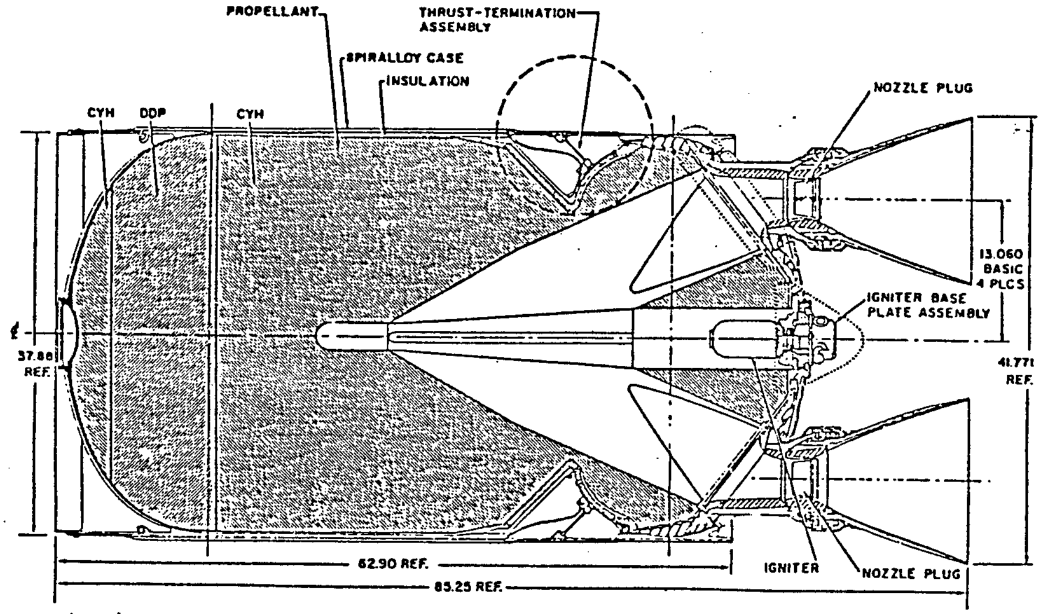

FIGURE 1. Minuteman II Stage III Rocket Motor

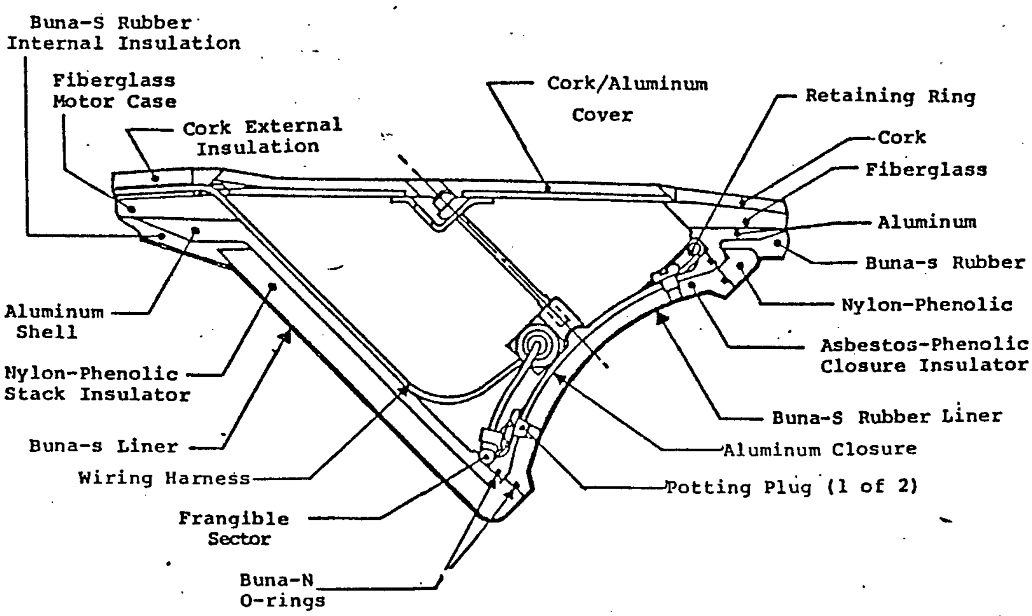

FIGURE 2. Thrust Termination Assembly

Because OO/ALC suspected the failures were caused by hot gas flowing from the motor chamber past the outer O-ring or around the potting plugs, the refurbishment program consisted of replacing the potting compound, the potting plug seats, and the O-rings. After refurbishing 14 motors, the procedure included a leak test in the thrust termination port area so motors exhibiting leaks could be repaired or removed from the deployed force.

Of the 258 motors refurbished by 31 August 1984, 8 Minuteman II motors had failed the leak test and were not returned to the deployed force. None of these eight motors leaked through the O-ring interface between the thrust termination port and the aluminum closure; therefore, they were not the type of leaks addressed by the refurbishment program. In contrast, they leaked between the aluminum shell and the surrounding nylon phenolic insulator, with the gas exiting between the fiberglass case and the thrust termination assembly. The effect of this type of leak on thrust termination performance is currently unknown.

Since incorporating the leak test, OO/ALC has fired only those motors that passed the leak test. To date, they've fired 31 refurbished motors without observing a failure of any type (25 Minuteman I and 6 Minuteman II motors).

DATA ANALYSIS

Table 1 presents the stage III thrust termination data for 456 flight tests and 391 static firings. It depicts the number of motors tested and the number that successfully completed thrust termination. The table does not include failures other than premature thrust termination. Note that the data in the table is stratified by motor age, motor type [B (Minuteman I) or F (Minuteman II)], and motor condition (refurbished or unrefurbished).

The analyses to date have assumed there is a cause-effect relationship between motor age and reliability, that B and F motors provide equally representative data, and that the refurbishment program addresses a specific failure mode. These assumptions have not been proven, and they provide the greatest degree of uncertainty in assessing thrust termination performance. After discussing the implications of each data grouping, a statistical analysis of the data will be presented.

TABLE 1. STAGE III THRUST TERMINATION SUCCESS RATE
(SUCCESSES/ATTEMPTS)

MOTOR AGE (MONTHS)	UNREFURBISHED ALL MOTORS	B MOTORS	F MOTORS	REFURBISHED ALL MOTORS*	B MOTORS*	F MOTORS
250				1/1	1/1	
240-249	1/1	1/1		1/1	1/1	
230-239				3/3	3/3	
220-229	1/2	1/2		3/3	3/3	
210-219	2/3	2/3		3/3	3/3	
200-209	5/5	5/5		5/5	3/3	2/2
190-199	1/1	1/1		10/10	8/8	2/2
180-189	6/8	6/8		4/4	3/3	1/1
170-179	6/6	6/6				
160-169	8/8	6/6	2/2			
150-159	11/12	9/9	2/3	1/1		1/1
140-149	9/10	6/7	3/3			
130-139	10/10	9/9	1/1			
120-129	15/16	9/10	6/6			
110-119	18/19	15/16	3/3			
100-109	35/35	26/26	9/9			
90- 99	23/24	15/16	8/8			
80- 89	25/25	20/20	5/5			
70- 79	33/34	27/28	6/6			
60- 69	43/43	23/23	20/20			
50- 59	41/42	27/28	14/14			
1- 49	404/404	253/253	151/151			
0	108/108	104/104	4/4			
0-250	805/816	571/581	234/235	31/31	25/25	6/6

* Includes 6 refurbished motors fired as verification tests of the TT port fix

Motor Age: OO/ALC stratified the stage III motors by age to determine if the failures were age related. In conducting analyses for OO/ALC, the Eyring Research Institute determined the failure rate is dependent on the age of the thrust termination port (99 percent confidence). Figure 3 depicts this trend, plotting the thrust termination success rate as a function of motor age in 20-month intervals. Note that the last point represents a 60-month interval because of the limited data available.

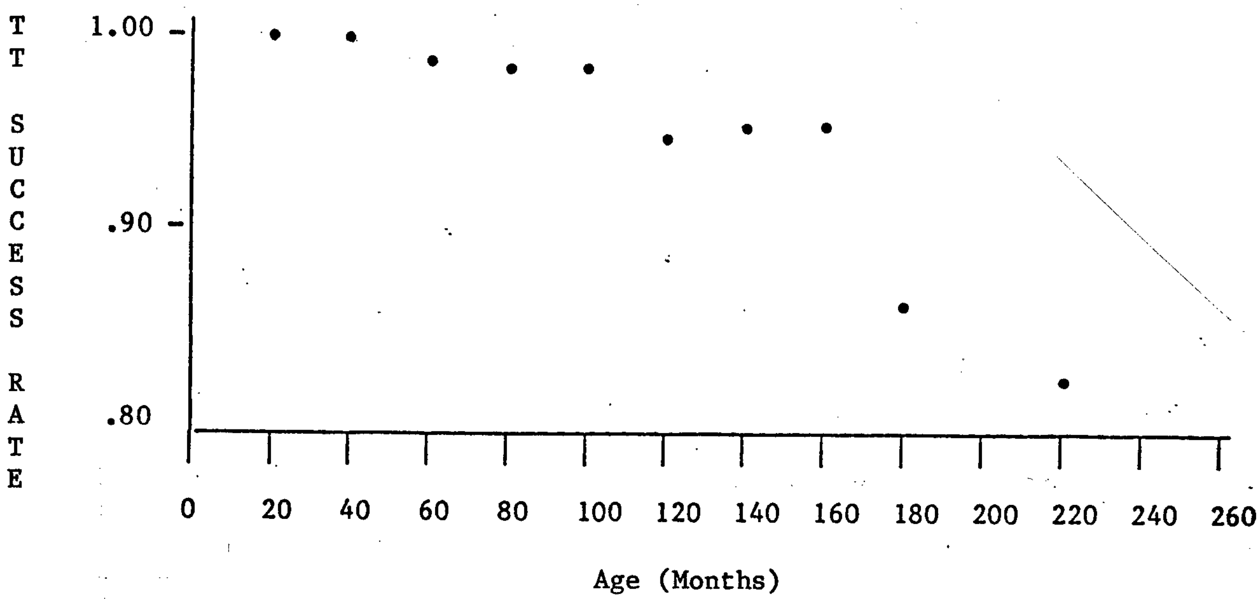

Figure 3. Stage III Thrust Termination Success Rate

There is no disagreement that the thrust termination port success rate is correlated with motor age. However, there is an important distinction between identifying a correlation and establishing a cause-effect relationship. Although it's intuitively appealing to speculate that the older motors are wearing out and becoming less effective, that hypothesis has not been proven. In fact, while the engineering community continues to search for the cause of an age-related premature thrust termination problem, certain engineers from the Hercules corporation maintain the failures are due to manufacturing defects. It remains possible, then, that there is no cause-effect relationship between age and reliability. If the failures are not caused by some sort of age-related degradation, the observed thrust termination failure rate is less than two percent (11/816).

Motor Types: Two types of motors contribute to the thrust termination data base. The B motors (LGM30B) are Minuteman I motors while the Minuteman II motors are referred to as F motors (LGM30F). Although the motors are slightly different, their thrust termination assemblies are identical. Consequently, thrust termination analyses have included data from both motors. However, 10 of the 11 thrust termination failures have occurred in the B motors; 6 in motors less than 150 months old, and 4 in motors 180 months old or older. The data implies the B motors may be affected by some sort of age-related degradation. In fact, a statistical comparison of B motors that are older than 170 months with the younger B motors reveals there is less than a one percent chance their thrust termination success rates are equivalent. On the other hand, there has been only one F motor failure in 235 tests of motors up to 170 months old. Comparing the data for B and F motors of similar age indicates there is an 81 percent chance their thrust termination success rates are different. Therefore, the premature thrust termination problem may primarily affect the B motors.

Motor Condition: The motors have also been separated according to whether they've been refurbished or not. Such a distinction presumes the refurbishment program causes a difference in thrust termination performance. Some of the engineers at OO/ALC believe the refurbishment does not affect motor performance and only serves to confound the data.

The engineers question the effectiveness of the refurbishment for two reasons: 1) they haven't been able to replicate the failure and 2) they haven't discovered any defects in the thrust termination assemblies they've refurbished. In trying to induce premature thrust termination, they tested a motor with an intentionally damaged O-ring and three motors with all the potting compound removed. These modifications should have induced the failure condition the refurbishment program was designed to correct, but the motors operated normally. The results of these tests indicate the postulated failure mode may not be a significant problem. The engineers' second point is they haven't seen any defective O-rings or potting compound in the thrust termination ports they've refurbished. Thus, in questioning the effectiveness of the refurbishment, the engineers doubt the program addresses the source of the problem.

If the refurbishment program is, indeed, unnecessary, then one must explain the 31 successful tests of refurbished motors. Some possibilities are:

1) Reliability was not as low as predicted and the effect of age may have been exaggerated, implying the failures might be due to manufacturing defects.

2) Reliability was as low as predicted and we've observed a highly unlikely string of successes.

3) The failure is related to motors that failed the leak test

4) Most of the defective motors have been tested, eliminating the failure mode by "attrition".

Note that if age is not a causative factor, the 31 successful tests of refurbished motors are not inconsistent with 805 successes in 816 tests of unrefurbished motors.

Others who believe the refurbishment program may have corrected an unknown problem are concerned over the life of the motor "fix". Since all the refurbished motors have been tested shortly after receiving their new O-rings and potting compound, there is no data available on the effectiveness of the refurbishment over time. Even if the refurbishment does improve motor performance, we can't estimate its effect after five or ten years.

Stratification Summary: As discussed above, the data have been stratified by motor age, type, and condition. These divisions appear to be logical, but the failure to identify the cause of premature thrust termination raises questions about the validity of each stratification. These questions must be considered when analyzing the data.

Statistical Analysis: The current analyses have assumed the stratifications are valid. To assume otherwise would render analysis unnecessary. If age is not a factor then the thrust termination success rate is .987. If B and F motor data are not compatible, then the F motor appears to be sound with only one thrust termination failure in 235 tests (.996). Finally, if the refurbishment program does not address a specific failure mode, then stratifying on motor condition is an artificial division of the motor data. Although not reflected in the statistics that follow, the questions concerning the stratification of the data present the largest uncertainties in assessing thrust termination performance.

Assuming motor reliability is a function of age, the probability of successful thrust termination is most likely between .80 and .88. At the lower end of the spectrum, there has been a .800 success rate of unrefurbished motors with ages similar to those of refurbished motors (16/20 motors at least 180 months old). A second estimate is obtained by separating the data into homogenous groups. Figure 3 and Table 1 indicate age groups 0-49, 50-109, 110-169, and above 170 months have distinctly different reliabilities. The latter group consists of 22 successes out of 26 tests, a success ratio of .846. With the mean age of refurbished motors being 206 months, an OO/ALC regression based on motor age yields the highest estimate of .873.[1] With a range of .80 to .88, this analysis assumes a thrust termination reliability of .85 for an unrefurbished motor.

In contrast, the refurbished motors have not failed in 31 tests. These successful tests indicate refurbished motors are more reliable than unrefurbished motors. If the reliability of the refurbished motors was .85, there would only be a 0.6 percent chance of observing 31 successful tests without a failure. In other words, there is less than a one percent chance of incorrectly concluding motor reliability improved over the previous estimate. Therefore, there is 99.4 percent confidence that motor reliability is better than the .85 estimate for the unrefurbished motors.

The above comparison clearly indicates with high statistical confidence that recently refurbished motors perform more reliably than unrefurbished motors. However, this comparison is based on assumptions that have not been proven. If there is not a cause-effect relationship between motor age and reliability, if the B and F motor data cannot be treated as one data set, or if the refurbishment program does not correct a failure mode, the preceeding statistical analysis becomes meaningless. Since there is a high degree of uncertainty in the underlying assumptions, it would be worthwhile to examine how changing the assumptions affects the stage replacement decision.

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1. $R = e^{-(2.0801431 \times 10^{-6})(\text{motor age})^{2.080646515}}$

SENSITIVITY TO ASSUMPTIONS

The testing to date has not resolved the questions concerning the three assumptions about the motor data. It remains possible that the failures could be either age-related or the result of manufacturing defects. Similarly, test results have not eliminated the uncertainties regarding the effect of the refurbishment program. Finally, no one has determined whether or not it's appropriate to pool data from the B and F motors. Therefore, it may not be fruitful, or even possible, to prove a particular set of assumptions. However, the available information can lead to logical conclusions if the analysis uses sets of consistent assumptions and the data we're most confident in.

Figure 4 outlines two sets of assumptions and the conclusions that follow. The branch on the left begins with the assumption that the thrust termination failures in the B motor are age-related. Under this assumption, the thrust termination success rate in the unrefurbished B motors is about .85 while the refurbished motors have exhibited a success rate of 1.0. With 25 refurbished B motor tests, there is a 98.3% confidence that the refurbished B motors perform more reliably than the unrefurbished B motors. Therefore, if the B motors are degrading with age, refurbishment effectively eliminates the problem. It would be inconsistent to accept the statistical argument that the B motors are degrading with age while ignoring the statistics that imply refurbishing the B motors is effective.

To apply the information about the B motor to the F motor requires the assumption that they are basically the same motor and experience similar problems. In this case, the high confidence in the effectiveness of refurbishing the B motor translates into an equally effective program for the F motor. In fact, the statistical confidence in refurbishment increases to 99.4% when combining the B and F motor data.

On the other hand, the opposite assumption precludes using B motor failures to predict an F motor degrade. Without the B motor data to indicate a decreasing thrust termination success rate, there is no evidence of a problem in the F motor. Therefore, assuming the failure in the B motor is age-related leads to the conclusion that either refurbishment will correct the problem in the F motor or that the F motor is not degrading with age.

Assuming the B motor failures are not age-related leads to the second set of assumptions. Disregarding motor age implies the failures are due to a manufacturing defect. This assumption is also consistent with the OO/ALC engineering assessment that the refurbishment has no effect on the thrust termination success rate. However, the effect of refurbishment as well as the differences between the motors are largely irrelevant due to the high thrust termination success rates in unrefurbished motors (B = .983, F = .996, combined = .987). Consequently, if the failures are not related to age, the low failure rate does not indicate a significant problem in either the B or the F motor.

Therefore, the stage replacement decision is not sensitive to the basic assumptions because the two different sets of assumptions yield the same conclusion. Varying the assumptions leads to either confirming the effectiveness of the refurbishment program or denying a degradation affects the F motor. In either case, the data do not support replacing the Minuteman II Stage III.

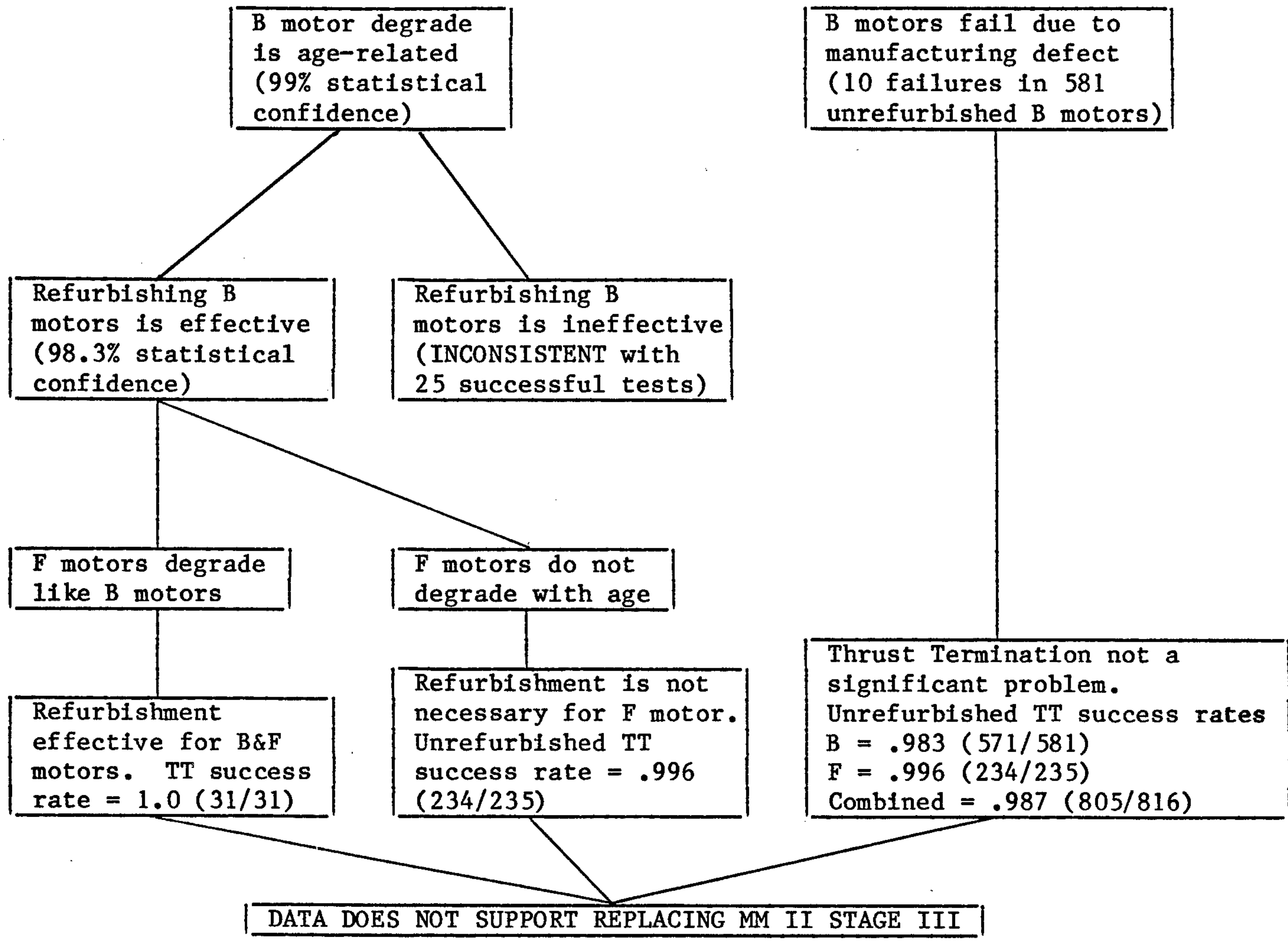

Figure 4. Assumptions Regarding the Minuteman II Stage III

OBSERVATIONS

1. Statistical analysis reveals there is a strong correlation between motor age and reliability. There is also approximately 99% statistical confidence that the recently refurbished motors perform more reliably than unrefurbished motors.

2. The assumptions about the underlying data provide the greatest degree of uncertainty involved in comparing the performance of refurbished and unrefurbished Minuteman I & II stage III motors.

3. The value of statistical analyses based on uncertain assumptions is questionable; however, the conclusions drawn from the data are not sensitive to changes in the assumptions as long as the assumptions are consistent.

4. Sets of consistent assumptions lead to the conclusion that either refurbishing the Stage III is effective or the F motor is not degrading with age.

5. The data do not support replacing the Minuteman II Stage III based on thrust termination considerations.

APPENDIX I

FACT SHEET

MINUTEMAN II - LGM 30F

Initial Deployment: Oct 1965

Deployment Locations:

Malmstrom	- 150
Ellsworth	- 150
Whiteman	- 150
	450

Physical Dimensions (feet)

	Diameter	Length
Missile	variable	57.6
Stages		
I	5.5	24
II	4.3	14
III	3.0	7

Missile Weight: 74,000 lbs

Propellant: 3 solid fuel motors

Guidance: Inertial (NS17)

Reentry Vehicle: Mk 11C

Flight Description: After launch from the underground silo, the missile rises vertically for several seconds and then begins a programmed pitchover program. During the second and third stages of flight yaw and roll are controlled for fine alignment. The missile reaches speeds in excess of 16,000 mph. At termination of third stage thrust, the reentry vehicle separates and continues on to the target.